REMOTE AREA CLEARENCE DEVICE

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Abstract

This report summarizes the motivation, designing, and research findings of the Remote Area Clearance Device (RACE). RACE is a Bluetooth controlled robotic car that comes equipped with a metal detector, a depth camera, and a retrieval unit that allows the user to safely dispose of small objects on the ground. The metal detector is based on the Colpitts Oscillator design, and uses the principles of inductance and magnetic permeability of objects. The retrieval unit is composed of a brush and scooping system connected to the car by a robotic arm powered by a digital servo motor. The scooping system is a 3D printed container equipped with a DC motor to power the bush system The results show that the metal detection system works well for larger objects, but needs to be researched more before it can be made reliably used.

Contents

1. Introduction

Improvised Explosive Devices (IED) and mines pose significant threat to the United States Army, with regard to engineering operations and maneuver support [1]. This project was aimed at addressing this issue, by developing a robot that can detect metallic objects, and perform some task on detection. The second aspect of this research, which was supported by the US Army Construction Research Laboratory, was to find whether a Colpitts Oscillator Design can be used to determine the metallic properties of an object. As a first step, we built a Bluetooth controlled car that can detect metal objects and retrieve them using a brush and scoop mechanism. By using a servo motor to lower a container and a DC motor to spin a brush which pushes objects into this container, we were able to build a functioning retrieval system. However, we the results show that the Colpitts Oscillator design is too unreliable to be used alone.

2 Design

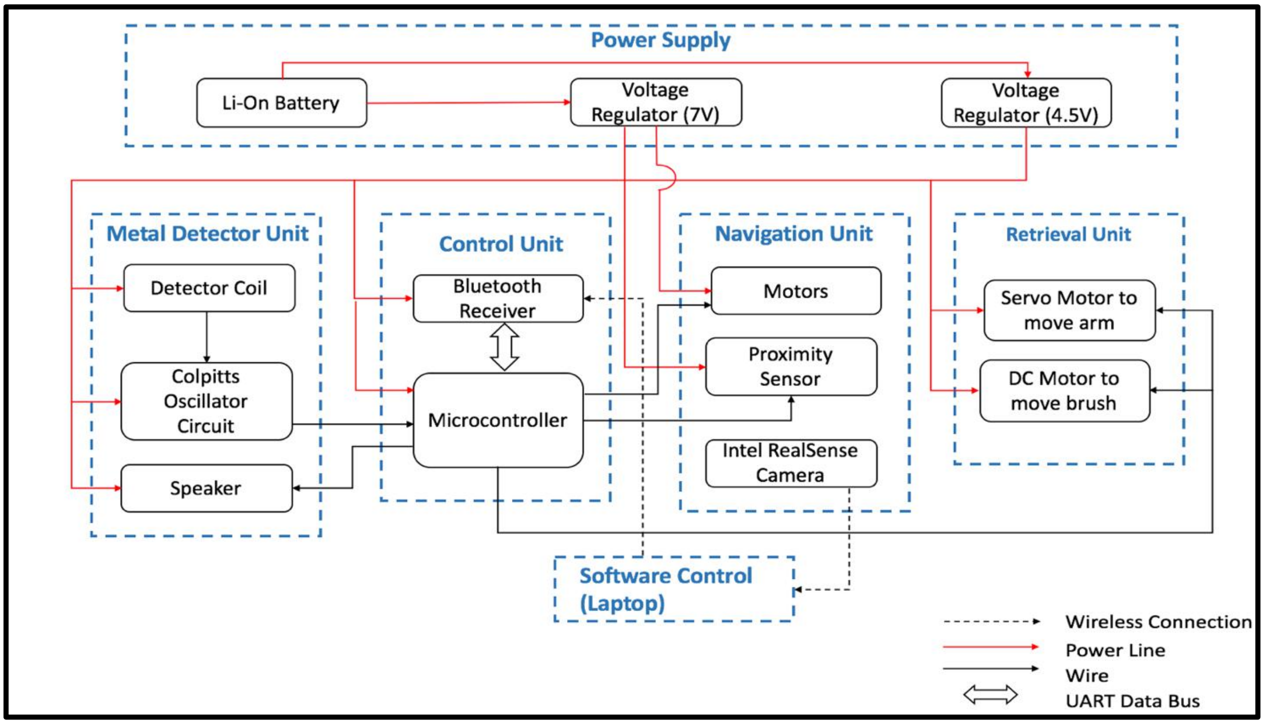

Figure 1: Block Diagram

2.1 Power Module

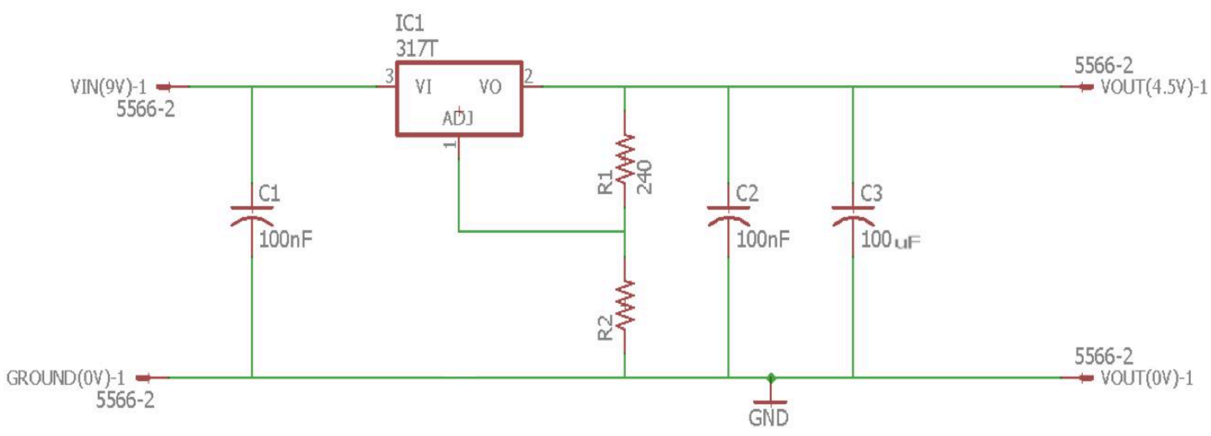

Figure 2: Voltage Regulator Circuit Schematic [2]

The circuit requires two different voltage buses. A 7V supply was needed for the Servo motor and the 2 navigation DC motors. A 4.5V supply was needed for the Bluetooth module, microcontroller, H-bridges, DC motor for brush and the Colpitts Oscillator.

Two LM317T adjustable positive voltage regulators were used to provide a the 4.5V and 7V voltages from an 11.2V Li-On battery. The LM317T is capable of supplying a maximum of 1.5 A. The maximum current draw for the robot, when all motors were operational was 0.64 A. The battery holds an energy charge of $2200\ \mathrm{mAh}$. This ensures at least $3.4\ \mathrm{hrs}$ of operation, which is well above our requirements.

Figure 2 shows the circuit design for the voltage regulator. The reference voltage across resistor R1 is constant at 1.25V. The adjustment terminal current is $100\ \mu\mathrm{A}$, which corresponds to a minimum value of 120Ω for resistor R1. The output voltage is calculated as

$$\mathrm{V_{OUT}} = 1.25\times\left(1+\frac{\mathrm{R_2}}{\mathrm{R_1}}\right) \tag{2.1}$$

Using Equation (2.1), the value of resistor $\mathrm{R_2}$ was calculated to be 624Ω for the 4.5V regulator, and 1104Ω for the 7V regulator.

The value for resistor $\mathrm{R_1}$ was chosen as 240Ω to provide for better stability. Stability is essential for the 4.5V regulator, to minimize the fluctuation in frequency produced by the Colpitts Oscillator. The additional capacitors aid in the stability of the regulator, and help smooth out the inherent ripple content giving it a good transient response [2].

2.2 Metal Detector Module

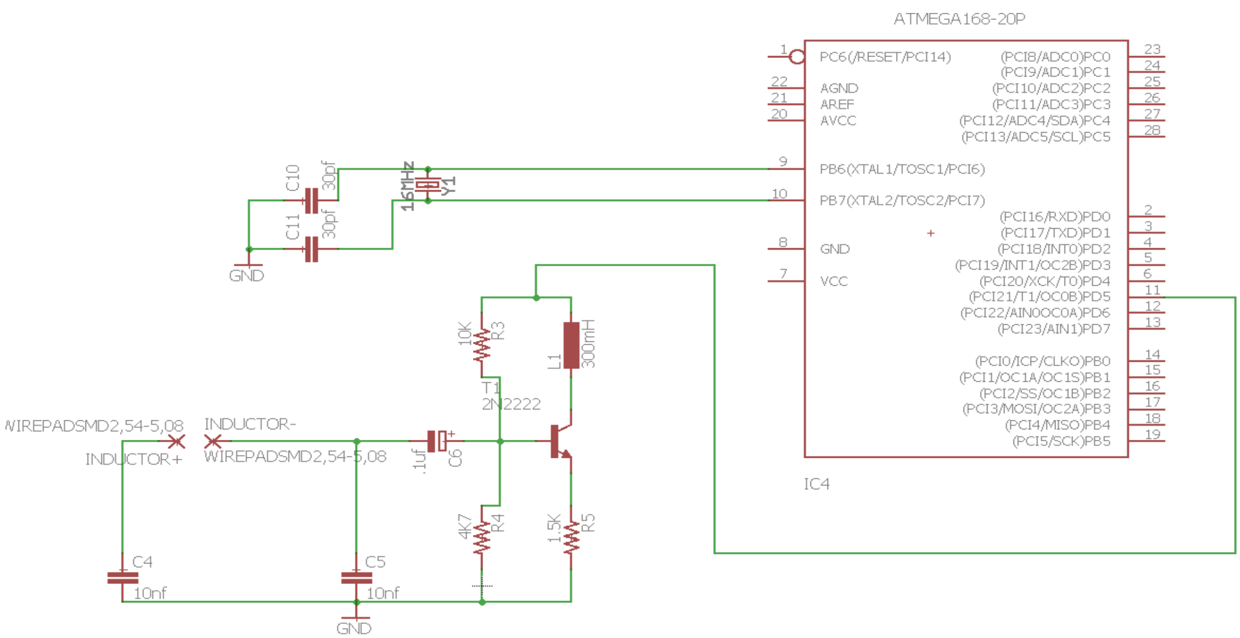

Figure 3: Metal Detector Circuit Schematic

The metal detection module utilizes a Colpitts Oscillator and a detector coil. The Colpitts Oscillator was used to produce a fixed frequency of 100 kHz using a combination of capacitors and an inductor. This frequency is continuously fed into the microcontroller. When the detector coil is brought neat a metallic object, its inductance changes which causes a shift in the frequency. This change is detected by the microcontroller, which then sends the user an alert through Bluetooth.

The speaker was removed from the proposed design. It was determined that a speaker is not the most reliable way to alert the user in a noisy and outdoor setting. It was also redundant since the channel of communication through Bluetooth was already implemented.

2.2.1 Colpitts Oscillator

The Colpitts Oscillator uses a capacitive voltage divider network as its feedback source and a single bipolar transistor amplifier (2N2222) as the gain element which produces the sinusoidal output. Figure 3 shows the circuit schematic for the metal detector module. The inductor is connected in parallel to capacitors C4 and C5 in series, to form the tank circuit. Once power is applied, the capacitors charge and discharge through the inductor. The voltage developed across capacitor C5 provides the regenerative feedback required for sustained oscillations [3]. The oscillations appear amplified at the collector output of the transistor, and are fed into the counter pin of the microcontroller. Resistors R4 and R5 provide the stabilizing DC bias. Capacitor C6 prevents DC currents from going into the tank circuit [3]. The transistor and the capacitive feedback each provide a phase shift of $180°$ to achieve a total phase shift of 360°, an essential condition for oscillations [3].

This design was chosen over other variants such as the Hartley oscillator because this configuration results in less self and mutual inductance within the tank circuit, thus improving the stability within the oscillator [4].

A higher frequency was chosen because it is better at inducing Eddy currents in non-ferrous objects, which decrease the inductance and hence makes it more suitable for detecting smaller objects [4]. While a higher frequency has a smaller range, our project only required a range of $2-3\ \mathrm{cm}$ to function.

The frequency of the oscillations is

$$\mathrm{F}=\frac{1}{2\times\pi\times\sqrt{\mathrm{L}\times\mathrm{C_T}}} \tag{2.2}$$

where L is the inductance and C_T is the capacitance of the tank circuit. To produce a frequency of $100\ \mathrm{kHz}$, the capacitance and inductance were calculated as $5\ \mathrm{nF}$ and $0.506\ \mathrm{mH}$ respectively using Equation 2.2.

The values of the capacitance of the tank circuit is given by

$$\mathrm{C_T}=\frac{\mathrm{C_4}\times\mathrm{C_5}}{\mathrm{C_4}+\mathrm{C_5}} \tag{2.3}$$

where $\mathrm{C_4}$ and $\mathrm{C_5}$ are the two capacitors in the tank circuit (see figure 3). The feedback fraction is given by

$$\frac{\mathrm{C_4}}{\mathrm{C_5}}\% \tag{2.4}$$

A large amount of feedback returned the circuit can cause the sine wave to become distorted, and a small amount will prevent the oscillation from getting started [4]. Comparing Equations (2.3) and (2.4), $\mathrm{C_4}$ and $\mathrm{C_4}$ were both calculated as $10\ \mathrm{nf}$.

2.2.2 Detector Coil

The detector coil is an inductor made up of 24AWG wire wrapped around a hollow, non-conductive spool. The inductance of the coil is calculated as

$$L = \frac{N^2 \times \mu \times A}{l} \tag{2.5}$$

where N is the number of turns in coil, A is the area of the coil, l is the length of the coil and μ is the permeability of free space. Using Equation 2.5, the number of turns was found to be 50, radius to be $5.08\ \mathrm{cm}$ and the length to be $2.032\ \mathrm{cm}$.

When a metal with high conductivity (such as silver) is brought near the coil, its magnetic permeability increases which causes an increase in its inductance [5]. When a metal of low conductivity is brought near the coil, Eddy currents are induced in the metal, which oppose the electric field of the inductor [5]. This causes a decrease in inductance, which increases the frequency produced by the Colpitts Oscillator [4].

This design worked for larger objects, but the change in frequency was too small to detect for smaller objects. Thus, a new inductor was built which had a magnetic field 4 times as strong as the original one, and an inductance of $10\ \mathrm{mH}$ (the capacitors values in the tank circuit were adjusted to keep the frequency constant). The magnetic field of an inductor is given by

$$B = \frac{N \times \mu \times I}{L} \tag{2.6}$$

where N is the number of turns in the coil, μ is the magnetic permeability of free space, I is the current in the inductor and L is the length of the inductor. This inductor's dimensions were calculated by comparing the Equation (2.6) and (2.5).

2.3 Control Unit

The control unit is used to control the operation of the robot's functions. It consists of a Bluetooth Module and a Microcontroller chip.

2.3.1 Bluetooth Module

The Bluetooth module is used to wirelessly send data to the microcontroller so that the robot's functions can be remotely controlled. The HC-05 Bluetooth transceiver was chosen due to its excellent range of over $40\ \mathrm{ft}$, and its relatively cheap cost. The Bluetooth module receives data from an android app, and communicates with the microcontroller over UART interface at a baud rate of 9600 bps. As we only send a single byte of information at a time, speed of data transfer was not a concern.

HC-05 has can tolerate a maximum input signal of 3.3 V, which is lower than the output signal of the ATmega328 microcontroller. Thus, a voltage divider made up two resistors of values $1000\ \Omega$ and $2000\ \Omega$ was used to connect the RX pin of the module to the TX pin of the microcontroller. Figure 4 shows the circuit schematic for the Bluetooth module.

The HC-05 Bluetooth module cannot connect to Apple devices. We searched for other modules, but found out that Apple devices can only connect to Bluetooth devices registered with the firm. We were unable to find any inexpensive stand-alone Bluetooth module that can connect to Apple devices.

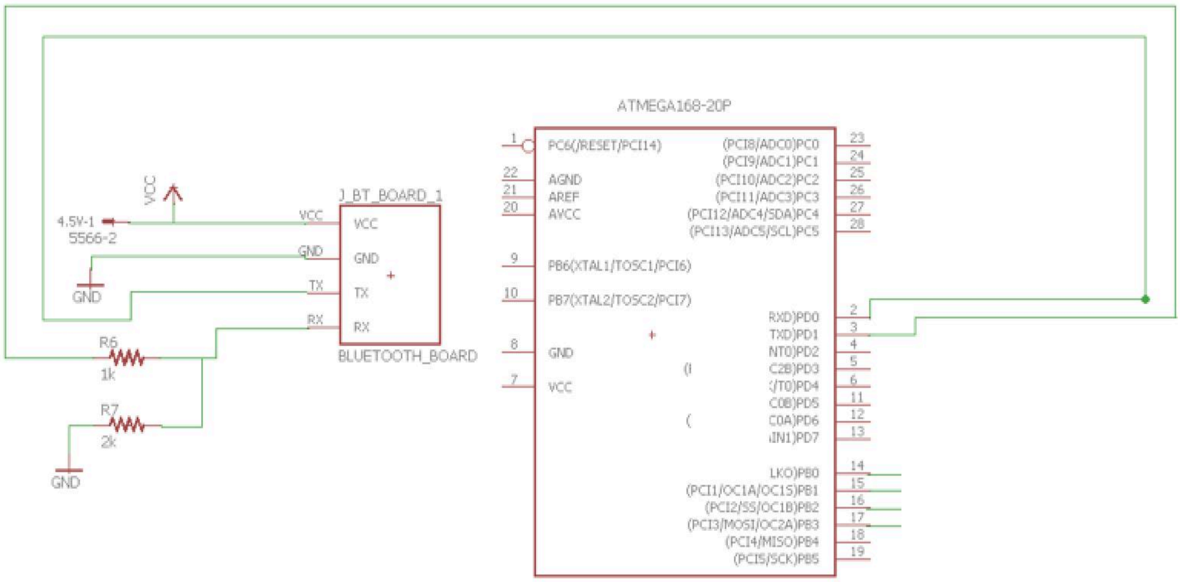

Figure 4: Bluetooth Module Circuit Schematic

2.3.2 Microcontroller

ATMega328P-U was chosen to be our robot's microcontroller due to its inexpensive cost. The microcontroller receives the data from the Bluetooth module, decodes it, and performs the appropriate function on one of the motors. The microcontroller controls the two DC motors for navigation, the upwards and downwards movement of the Servo motor, and the DC motor for the brush.

The Signal input of the Servo motor was connected to Port B, as it requires a PWM wave in order to have precise control over the degree of rotation.

Additionally, the microcontroller continuously reads the frequency of the Colpitts Oscillator, and compares it with the fixed frequency of $100\ \mathrm{kHz}$. When the frequency changes by more than the average fluctuation, a message is sent to the app through Bluetooth to alert the user that metal has been detected.

2.4 Navigation Unit

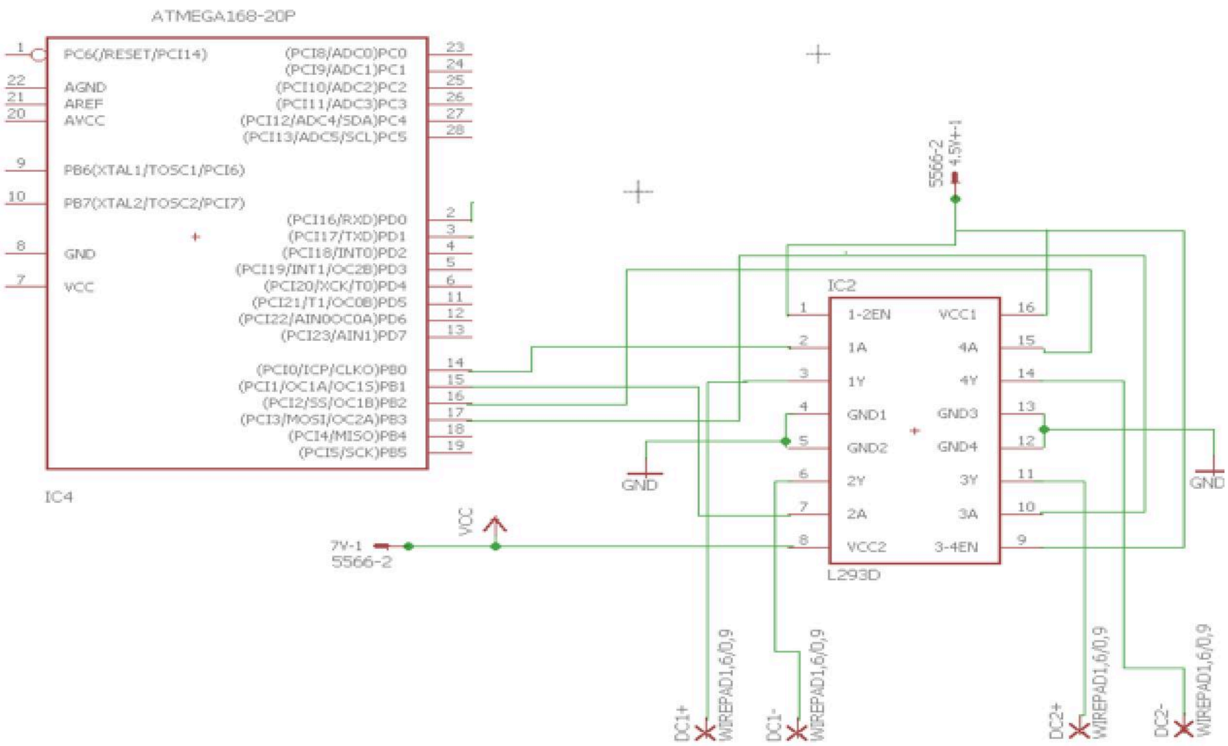

Figure 5: Navigation Unit Circuit Schematic

The navigation unit controls the motion of the robot using two DC motors for the two wheel tracks. Since DC motors are an inductive load, the motors were driven using the L293D H-bridge as the pins of the ATMega328 can handle a maximum current of $40\ \mathrm{mA}$. The positive and negative pins of the both motors were connected to the H bridge, which receives its input from the Port B of the Microcontroller. Thus, each motor can be driven forward and backwards. The robot is able to turn left and right by moving the motors in the opposite direction. Figure 5 shows the circuit schematic of the navigation module.

The navigation unit also has an Intel RealSense camera, which is mounted on the robot. The purpose of the camera is to aid in navigation by providing real time video feedback to the user. The camera sends the video stream over its own Wi-Fi network, which can be viewed in the app. This camera was chosen due to its advanced functionalities such as depth analysis and facial recognition. The next step in the project is to use these capabilities to implement semi-autonomous navigation.

2.5 Retrieval Unit

The retrieval unit is used to retrieve small objects from the ground. The unit consists of a Servo motor, two wooden arms, a 3D printed container, a brush and a DC motor to rotate the brush. Figure 6 shows the Physical CAD Design of the retrieval unit.

In the initial design, the coil was in front of the retrieval unit, on the same side of the car (see Figure 6). However, this orientation caused an imbalance in weight which caused the robot to tip over. Thus, the detector coil was place at the back of the robot to balance the weight.

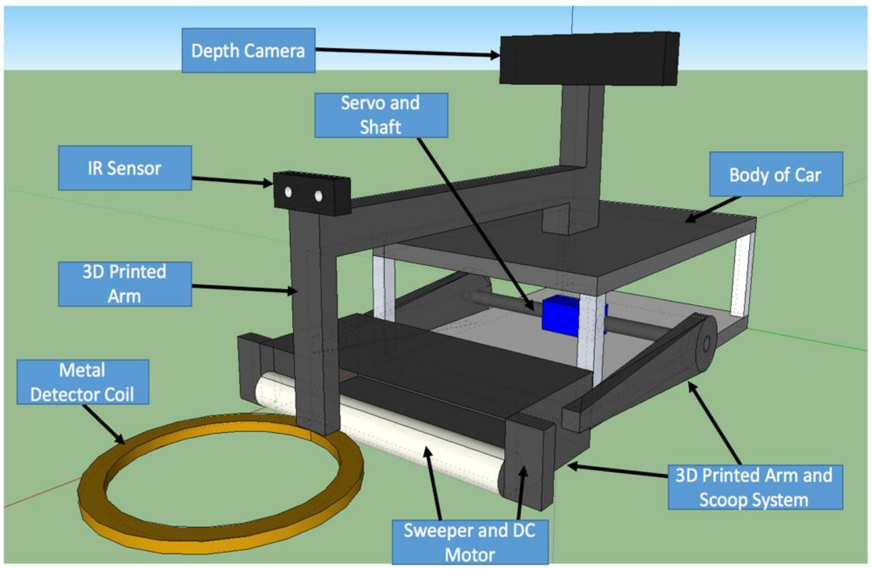

Figure 6: CAD Design of the Robot with the Retrieval Unit

2.5.1 The Scoop System

The 3D printed container is 9 cm wide and is connected to the two wooden arms which are connected to the Servo motor. The microcontroller rotates the servo motor, which enables it to lower the container until it lays flat on the ground. To provide some flexibility to the container and to add robustness, springs and stoppers were added to the back of the container at its connection point with the arms. This allowed the container to adjust to small variances in the gradient of the terrain. These rubber stoppers also prevent the container from smashing too hard on the ground, thus reducing the risk of the system breaking apart.

The position of the servo motor is updated by 1 degree at a time, in order to provide a continuous, jerk-free motion. This reduces the possibility of the object dropping from the container when it is being scooped up.

Keeping in mind that we would design a bigger retrieval unit in the future, a high torque Servo motor of Torque 20 kg-cm was chosen so that larger objects could be picked up.

2.5.2 The Brush System

The container has a horizontally positioned brush attached in front of it which is connected to a DC motor. This motor spins the brush, which pushes an object into the container. A brush with thick plastic hair was chosen so that it can push the object with a stronger force. The brush hangs $1.3\ \mathrm{cm}$ from the base of the container. Thus, the maximum height of the objects that can be retrieved is $1.3\ \mathrm{cm}$.

Initially, the DC motor chosen was high speed motor. It drew $1.2\ \mathrm{A}$ of current, and would cause the navigation motors to slow down if operated simultaneously. It also had a low torque, and would get stuck if the object was heavy. This motor was replaced with a high torque DC motor, which ran at $10000\ \mathrm{RPM}$. The new motor was able to provide the object with enough momentum to overcome the frictional force acting on it.

In order to prevent the objects from falling down when the container was being lifted up, a small bumper was built on the base of the container at a small incline. This incline did not stop the object from entering the container, but prevented them from falling out. The base of the container was made as thin as possible ($1\ \mathrm{mm\ thick}$) while maintaining the structural integrity, to allow the system to pick up flat objects such as keys.

2.6 Software Control

In order to control the functions of the robot, an android app was developed. This app used the phone's Bluetooth client to connect to the HC-05 Bluetooth module. There are four push down buttons to control the navigation system and drive the robot forward, backward, left and right. There were four on click buttons to control the retrieval unit; two to rotate the servo motor up and down, and the other two to start and stop the brush.

Our proposed design did not include a mobile application. The robot was meant to be controlled through a laptop. We did not think it was feasible to control the robot with a laptop as the robot has a range of over $30\ \mathrm{feet}$. Thus, an android app was developed to provide a better user experience.

3 Verification

3.1 Power Module

The results for the two voltage regulators are shown in Table 1.

Table 1: Voltage Regulator Results

Regulator	Observed Voltage	Maximum Fluctuation over a Period of 30 minutes
4.5V	4.52V	0.44%
7V	7.1V	1.12%

3.2 Metal Detector Module

3.2.1 Colpitts Oscillator

A frequency of 98.614 kHz was observed with an error margin of 0.57% using the initial design. This signal was sustainable, and remained in this range for at least thirty minutes. This was within our acceptable limits. Figure 7 shows the Oscilloscope reading of the signal. Figure 8 shows the same signal when the inductor is close to a metallic object of Volume $110.12\ cm^2$.

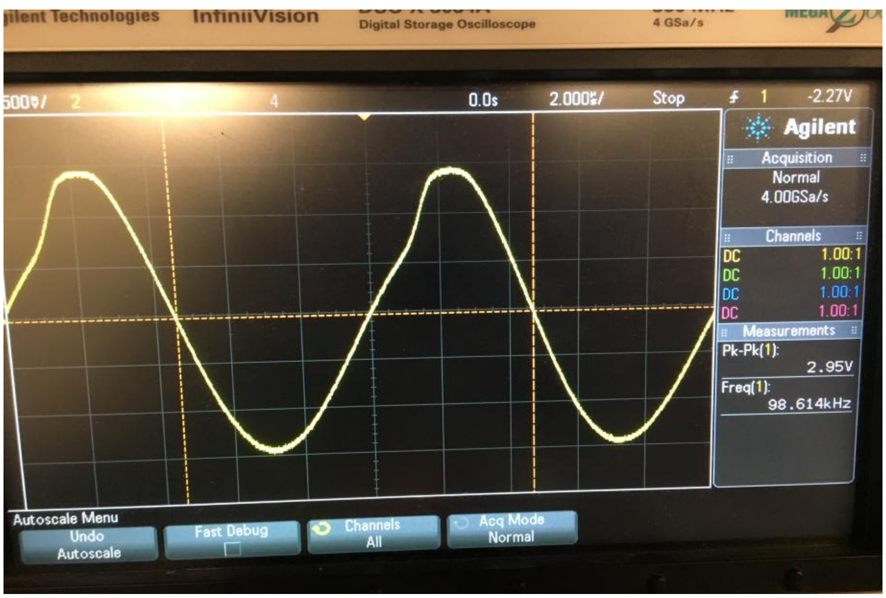

Figure 7: Oscilloscope Reading of 98 kHz signal

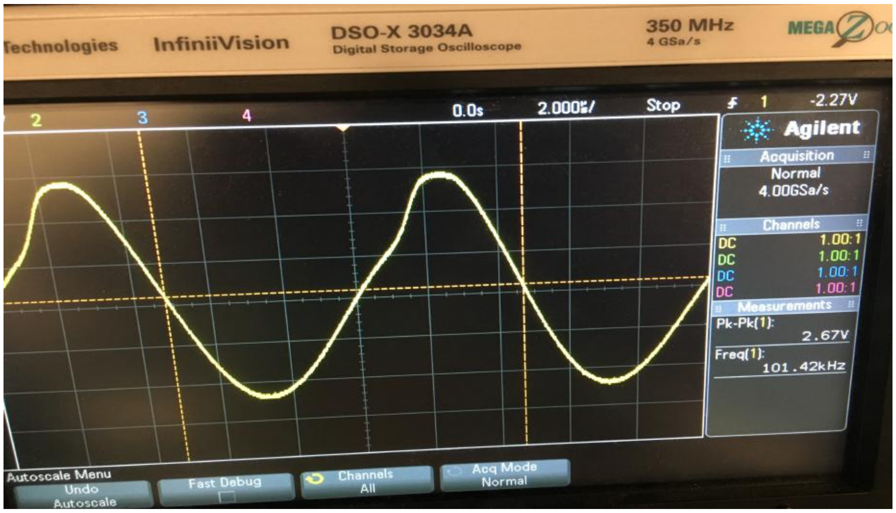

Figure 8: Signal Wave on Oscilloscope when the object is near a metallic object

3.2.2 Detector Coil

With the initial design, the smallest object that could be detected was a cuboid of length 3 cm, width 1.5 cm and height 2.7 cm. This was bigger than the minimum size requirements for our design. Thus, a new inductor was built with a magnetic field four times as strong as the previous one. Along with this, different frequencies were tested, the results of which are shown in Table 2.

Table 2 The Change in frequency for Different Frequencies

Inductance (mH)	Capacitance (nF)	Observed Frequency (kHz)	Fluctuation Percentage	Percentage Change due to brass object of Volume $4.92\ cm^2$	Percentage Change due to brass object of Volume $110.12\ cm^2$
0.546	5	98.6	0.57	-	1.92
0.546	2.5	143.4	0.88	1.02	2.38
10	5	21.8	0.49	-	1.14
10	2.5	36.2	0.66	-	1.34
10	0.235	94.4	0.84	1.17	2.37

The new inductor did not satisfy the design requirements of the minimum object size either. The results show that while a stronger magnetic field increases the change in frequency, the increase in accuracy is marginal. Frequency plays a bigger role in determining the minimum size of the object that can be detected.

A test to compare the change in frequency at different distances from the inductor was also conducted for the two objects. The first object was a cuboid brass object of volume $4.92\ \mathrm{cm}^2$. The second object was a brass cylinder of volume $110.12\ \mathrm{cm}^2$. These are referred to as Object 1 and Object 2 respectively in Figure 9, which shows the frequency against the distance of the object from the inductor. We found that the large object (Object 2) could be detected at a maximum distance of 4 cm, whereas the smaller object (Object 1) was able to be detected at a maximum distance of 1 cm.

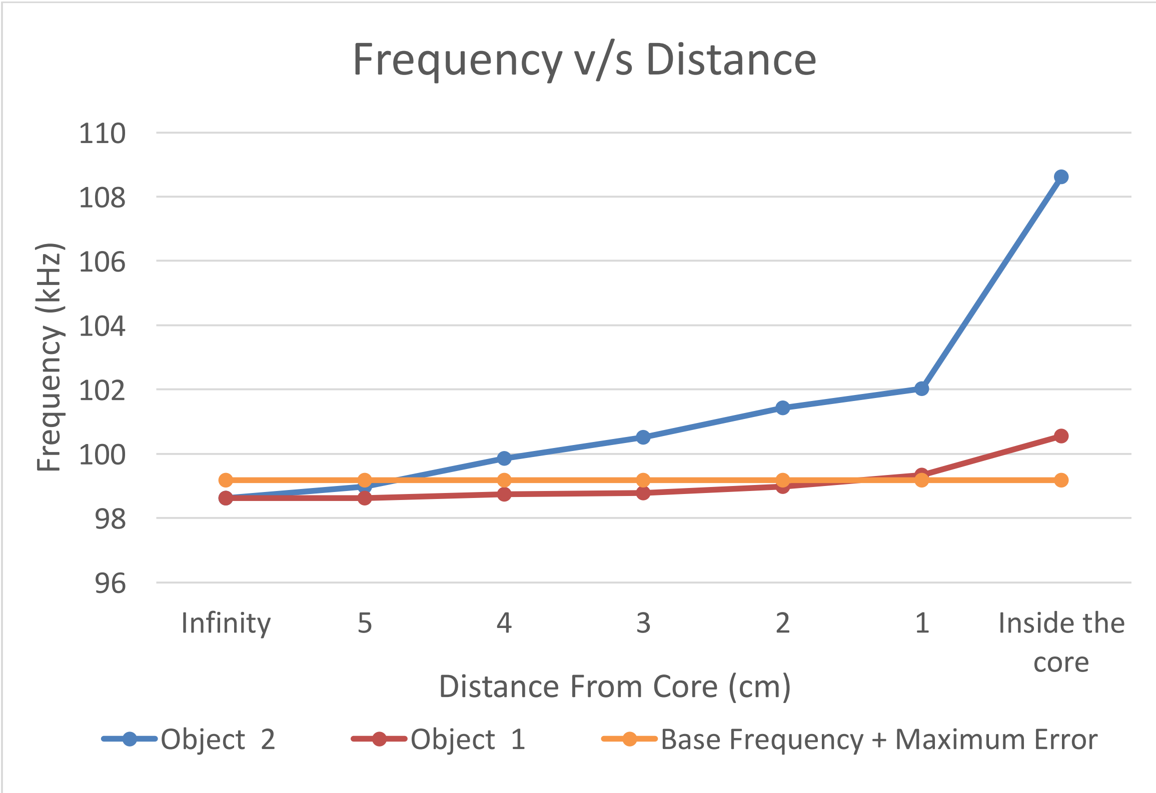

Figure 9: Relationship between change in frequency and distance from inductor

3.3 Retrieval Unit

The retrieval unit was tested with several objects of different shapes and sizes. Table 3 shows the different objects which were used as test cases. Each of these objects was tested 15 times. The results for the retrieval unit are shown in Figure 10. The system worked very well for nails and bolts, which was the requirement in our proposed design. The system struggled to pick up large cubical objects such as Lego pieces, as they would sometimes get stuck under the brush depending on the angle of approach.

Table 3: Test Cases for the Retrieval Unit

Object Name	Shape	Dimensions
Washer	Thin and flat	Height = 0.3 cm, Radius = 1.7 cm
House Key (with small key ring)	Thin and flat	Thickness = 0.3 cm, length = 3.1 cm
Bolt	Round – able to roll	Diameter of Head= 1.27 cm, length = 1.9 cm
Screw	Round – able to roll	Diameter of Head= 0.9 cm, length = 5.8 cm
Lego block	Cube – not able to roll	Side = 1.2cm
Car Key	Misc. – not able to roll	Height = 2.2 cm, Length = 5 cm, Width = 3 cm

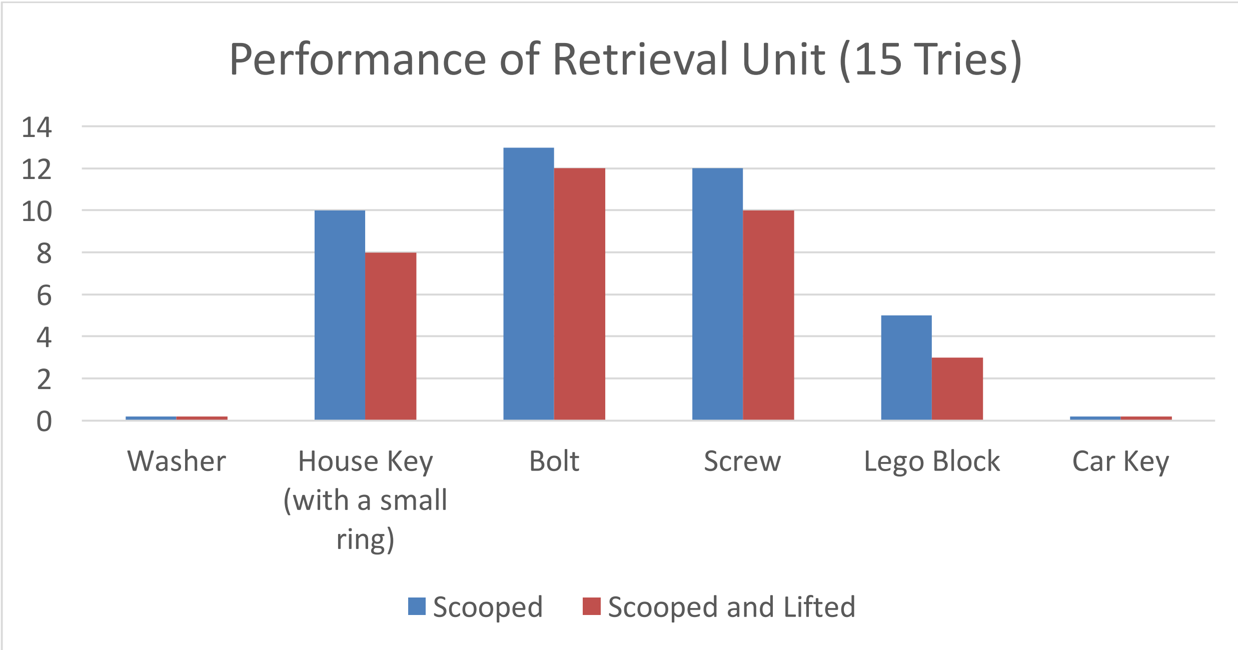

Figure 10: Results For the Scooping and Lifting of Various Objects

3.4 Control Unit

3.4.1 Bluetooth Module

Series of data was sent to the microcontroller which was being displayed on the Serial Monitor. It was verified that the correct data was received. The range of the Bluetooth Module was verified to be at least 35 feet.

3.4.2 Microcontroller

The Microcontroller was able to control the navigation unit, and communicate with the Bluetooth module.

Since the design of the Colpitts Oscillator was not finished until much later in the course, the code to read the frequency correctly into the microcontroller was tested using a sine wave generated by a function generator. The function was also displayed on the oscilloscope and it was verified that the frequency was being read correctly by the AtMega328.

This same code did not work with the Colpitts Oscillator. Due to the time constraints, we were not able to fix this error. We believe that the cause of this error was the fact that the signal was not sampled correctly, thus resulting in an incorrect reference DC voltage. The wave generated by the function generator is close to a perfect sine wave, which is why this error was not seen in the initial tests. In the case of a Colpitts Oscillator, the wave is not a perfect sine wave, and incorrect sampling could be the potential cause of the errors.

3.5 Navigation Unit

We verified that the car could drive forward, backward, left and right at a speed of at least 2.5 inches/sec, with the full weight of the retrieval unit and the metal detector.

3.6 Software Control

It was verified that the App could connect to the Bluetooth Module and control all operations of the robot.

4. Costs

Our labor cost is estimated at an hourly rate of $35 per hour, 12 hours per week for two people. The project was 12 weeks long. The total labor costs are given by

$$Total\ Cost = 2\times\frac{\$35}{hour}\times\frac{12\ hours}{week}\times 12\ weeks\times 2.5 = \$25{,}200 \tag{4.1}$$

Table 4 shows the cost of the parts used in making the project.

Table 4: Cost Analysis of Parts

Part	Manufacturer	Quantity	Retail Cost ($)	Bulk Purchase Cost ($)	Total Prototype Cost ($)
Chassis and Motors	Mountain Ark	1	49.99	44.99	49.99
Servo	LewanSoul	1	21.99	20.99	21.99
Bluetooth HC-05	DSD Tech	1	9.99	7.99	9.99
ATMega 238-PU	Atmel	1	2.28	1.68	2.28
LiPo Battery Pack	Turnigy	1	10.99	10.99	10.99
LM317T	Texas Instruments	2	2.03	1.38	4.06
24 AWG Wire	Remington Industries	75 feet	0.05	0.03	3.42
2N2222A NPN Transistor	McIgIcM	2	0.19	0.03	0.38
Intel RealSense D415	Intel	1	149.99	149.99	149.99
Assorted Components (Resistors, Capacitors, etc.)	KOA Speer	1	9.99	9.99	9.99
PCB	PCBWay	1	5.6	0.87	5.6
3D Printing	CERL	1	7.00	7.00	7.00
Total					275.68

Our total cost of part for the prototype is $275.68. Thus the total cost of development of a prototype is $\$275.68 + \$25{,}200 = \$25{,}475.68$.

5. Conclusion

5.1 Accomplishments

Our project worked as intended for the most part. The two major components of our system; retrieval and metal detection unit worked, even though their performance was not as good as expected. We were able to build a platform which has an easily expandable modular design. The techniques we have tested can be made more robust through further research and experimentation.

5.2 Ethical considerations

One of the ethical challenges posed by our project is the way it is used. Since it is a robot car that can be controlled wirelessly, a potential issue of trespassing property arises. The IEEE Code of Ethics states that one should avoid to injure other people and their property [6]. The car could also possibly injure people if it is not in the sight of the user during operation. We have equipped the car with a camera, so that the user can operate the car even it is not in their sight. To prevent the misuse of this robot, we have decided to use a Bluetooth receiver with limited range of about 40 feet. In order to prevent possible injuries to people and damage to property, we have used motors that limit the speed of the car to 2.5 inches per second.

The car uses a lithium ion battery, which poses a potential safety hazard. To prevent the battery from moving around during the operation of the car, it is securely placed on the chassis of the car.

Our project has two moving arms, and a rotating brush. To prevent possible injuries, we have limited the torque produced by the servo motor. The brush is rotated at a limited speed of 1 degree per second so that it may not injure anyone. Further, to ensure that no damage to property is done, the retrieval system is equipped with rubber stoppers so that the container does not smash into the ground.

We are also responsible for being honest about the claims we make about the project [6]. To adhere to this guideline, we will be very careful about the suggested usage of our product. Until it can meet the minimum accuracy guidelines for detecting landmines, the suggested usage would be strictly for home and recreational use.

The IEEE Code also states that one must hold paramount the safety of the public [6]. We believe that we have made an excellent cost effective platform, that can possibly help people in war torn regions. While its suggested use is in homes, its features can be expanded upon as the product is a great platform.

5.3 Future work

The next step in this project is to fully integrate the metal detector circuit we have built into our system, even though it does not work as we initially expected. We would then use the Depth Analysis feature of the Intel Camera in conjunction with proximity sensors in order to implement semi-autonomous navigation, so that the robot can look for objects itself with limited human control.

We would also like to build a more robust retrieval unit by experimenting with vacuum pumps, electromagnets, vertical brushes, and robotic arms to pick objects up. Finally, we'd like to test alternate metal detection techniques, such as capacitive sensing, beat frequency oscillators etc.

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Appendix A Requirement and Verification Table

Table 5: Retrieval Unit: Requirement and Verifications		
Sub-Module	Requirements	Status
Scoop System	1. The lower position of the arms should lay the container flat on the ground. 2. The stopper should be able to stop the arms when it reaches the ground, and prevent it from bumping into the inductor's holder while going up.	1. Item 1: Verified. 2. Item 2: Verified.
Brush System	1. The brush should be able to spin while hanging above the bottom edge of the scoop system by $0.5" \pm 5\%$. 2. The system should be able to pick up anything with dimensions of $(W \times D \times H)$ $3" \times 1" \times 0.5"$ with an accuracy of at least 75%. 3. The system should prevent objects from falling out of the container with a success rate of 80%.	1. Item 1: Verified. 2. Item 2: Verified. 3. Item 3: Verified.

Table 6: Power Module: Requirement and Verifications			
Sub-Module	**Requirements**	**Verification**	**Status**
Li-On Battery	1. The battery must be able to store enough charge to provide at least 640 mA current at 9V-11V, for at least two hours.	1. Verification Process for Item 1: a. Use a Voltmeter to verify that a Li-On battery supplies between 9-11V. b. Apply a consistent draw of 640mA against the battery pack for two hours, and ensure that that the voltage output is within the range 9V to 11V.	1. Item 1: Verified.
Voltage Regulator - 4.5V	1. The regulator should provide 4.5V $\pm$ 5% from an 9-11V source.	1. Verification Process for Item 1: a. Input Voltage: The circuit was connected to the power generator, which was set at 11V. The input voltage across was measured using a multimeter in DC voltage setting. This voltage was read to be 11V. b. Output Voltage: The output voltage was measured using a multimeter in DC voltage setting. This voltage was stable at 4.52V. c. Stability – The output voltage was measured while the input voltage from the power generator was reduced to 9V. The reading was stable	1. Item 1: Verified

Voltage Regulator - 7V	1. The regulator should provide 7V $\pm$ 5% from an 9-11V source.	1. Verification Process for Item 1: d. Input Voltage: The circuit was connected to the power generator, which was set at 11V. The input voltage across was measured using a multimeter in DC voltage setting. This voltage was read to be 11V. e. Output Voltage: The output voltage was measured using a multimeter in DC voltage setting. This voltage was stable at 7.1V. f. Stability – The output voltage was measured while the input voltage from the power generator was reduced to 8V. The reading was stable.	1. Item 1: Verified

Table 7: Navigation Unit: Requirement and Verifications			
Sub-Module	Requirements	Verification	Status
Motors	1. The DC motors must be able to operate at 7V±5%. The microcontroller must be able to control the movement of each DC motor. This includes turning it on/off, driving it forward and driving it backward.	1. Verification Process for Item 1: a. Power was applied to the circuit and the microcontroller was programmed to send the following signals to Pin 14, Pin 15, Pin 16 and Pin 17: LLLL - Both motors off HLLL – Left DC Motor forward LHLL – Left DC motor Backward LLHL – Right DC Motor Forward LLLH – Right DC Motor Backward	1. Item 1: Verified.
	2. They must be able to move the full weight of the car and the metal detector circuit, at a speed in the range of 2 to 2.5 inches per second.	2. Verification Process for Item 2: a. Using an inch tape, mark a distance of 5 ft., clearly marking the start and the end lines. b. The robot car, with all the modules attached, should be able to reach the endpoint from the start point in 24-30 seconds. c. Adjust the amount of voltage applied by changing the resistor values for the 7V regulator, until the speed is within the tolerance level.	2. Item 2: Verified.
Intel RealSense	1. The camera should be able to create its own Wi-Fi network, and	1. Verification Process for Item 2: a. Configure the camera	1. Item 1: Verified.

Camera	connect to a laptop with a range of at least 30 ft. 2. The camera should be able to transmit data over this Wi-Fi connection.	to create its own Wi-Fi network. b. Ensure that a laptop can connect to this network. c. Move the laptop at least 30 feet away from the camera. Ensure that the laptop can still connect the Wi-Fi network. 2. Verification process for Item 3: a. Connect the camera to a laptop, and turn its video feed on.	2. Item 2: Verified.

Table 8: Metal Detector Unit: Requirement and Verifications			
Sub-Module	**Requirements**	**Verification**	**Status**
Detector Coil	1. The magnetic field area created by the inductor coil should be big enough to give it a range of 3-5 cm.	1. Verification Process for Item 1: a. Place a screw nail of size 8D with a head diameter of 0.28 inches at a distance of 4-5cm away from the coil, while the circuit is being powered. b. Connect the collector pin of the amplifier to the oscilloscope. c. The change in frequency due to the metallic object must be greater than a threshold frequency, which will be found through experimentation.	1. Item 1: Failed. No change in frequency was observed due to small metallic objects such as nails, rings etc. A larger metallic object caused an increase in frequency of 2kHz.
Colpitts Oscillator Circuit	1. The oscillator circuit must provide a steady oscillation in the 100kHz $\pm$ 5% range when no metal is near the induction coil.	1. Verification Process for Item 1: a. Connect the collector pin of the amplifier to the oscilloscope. b. Apply 4.5V of power to the circuit, while ensuring that there is no metallic object within 20cm of the inductor coil. c. The frequency of the resultant sinusoidal signal should be 100kHz $\pm$ 5%. d. Adjust the capacitor values and the number of turns in the coil to	1. Item 1: Verified.

	2. The oscillation should be sustainable for at least two hours.	get the result within tolerance. 2. Verification Process for Item 2: e. Connect the output signal from the oscillator circuit to a frequency counter. f. Apply 4.5V of power to the circuit, while ensuring that there is no metallic object within 20cm of the inductor coil. g. The reading on the frequency counter should stay within 5% of 100kHz for at least two hours.	2. Item 2: Verified

Table 9: Control Unit: Requirement and Verifications			
Bluetooth Module	1. The Bluetooth receiver must be able to transfer data to and from the microcontroller over UART 2. It must have a range of at least 25 ft.	1. Verification process for Item 1: a. Configure the Bluetooth module with the microcontroller using the UART connection, by connecting the TXD and RXD pins to port D of the microcontroller. b. Set the baud rate to 9600 bps (default). c. Connect the Bluetooth module to a laptop. d. Send test data from the laptop. e. Verify that the test data was received correctly by the microcontroller. 2. Verification Process for Item 2: a. Connect the module to a laptop. The status LED should turn on. b. Move the laptop at least 25ft. away from the module. The LED should remain on.	1. Item 1: Verified. 2. Item 2: Verified.

Microcontroller	1. The microcontroller must be able to receive data from the Bluetooth receiver over UART. 2. The microcontroller must be able continuously compare the measured frequency and the fixed frequency, and trigger the speaker when the difference is greater than the threshold.	1. Verification process for Item 1: a. Configure the Bluetooth module with the microcontroller using the UART connection, by connecting the TXD and RXD pins to port D of the microcontroller. b. Set the baud rate to 9600 bps (default). c. Connect the Bluetooth module to a laptop. d. Send test data from the laptop. e. Verify that the test data was received correctly by the microcontroller. 2. Verification process for Item 2: a. Store an experimental threshold frequency (10kHz) and a fixed frequency (100kHz) in the microcontroller. b. Connect the port D of the microcontroller to the function generator in the sine wave mode. c. Configure the sine wave generator to generate a wave of 100kHz. d. Connect the speaker and configure the software so that the microcontroller triggers the speaker if the difference between the fixed frequency and the measured frequency is greater	1. Item 1: Verified. Item 2: Verified

		than the threshold. e. Now power the microcontroller chip. f. After 5 minutes, decrease the output of the function generator by 10kHz. The speaker should turn on.	